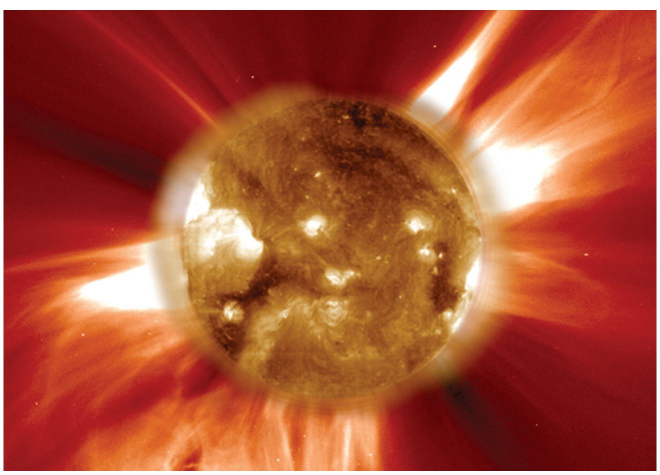
The Stuff That DREAM Is Made Of

Los Alamos physicist Geoffrey Reeves knows that the space just outside of Earth's protective atmosphere is a tempestuous, radiation-filled environment that can knock an orbiting satellite dead. So Reeves and a small team developed DREAM: software that gives satellite operators a heads up about the conditions surrounding their spacecraft and, thus, a chance to prepare for the worst of space-stormy weather.

In 1958, as the United States and the Soviet Union jockeyed for the lead in the newly inaugurated space race, a simple Geiger counter on the first U.S. satellite, Explorer 1, revealed that a belt of high-energy electrons and ions surround the Earth. Trapped by the Earth's magnetic field, the particles girdle the planet in a broad, donut-shaped cloud—the Van Allen radiation belt—and as it happens, nearly every commercial or military satellite flying today orbits either completely or partially within this radiation zone.

That's a problem. A fraction of the charged particles in the belt are relativistic (moving at an appreciable fraction of the speed of light), and relativistic electrons are a potent form of ionizing radiation. The electrons will blaze a trail of ionized atoms within almost any satellite material before losing enough of their energy to effectively come to a stop. They are notorious disrupters of computers and flippers of computer memory bits. The electrons can accumulate within a material, especially a dielectric, until they discharge as a spark. Furthermore, the electrons emit x-rays as they slow down. The x-rays fan out in all directions and effectively widen a single electron's sphere of potential damage to include the entire spacecraft.

But people are clever, and satellite engineers are generally able to counter the effects of an electron assault. They use radiation-hardened computer chips, shield critical electronics, rely on error-correcting software to repair data corrupted by radiation, and install redundant circuitry to compensate for hardware failures. These measures work well under normal circumstances. But then there are the storms.



The Sun ejects several billion tons of magnetized plasma into space on close to a daily basis, and when the plasma hits the Earth's magnetic field, it can result in any number of dramatic events. For example, an eruption in 1989 caused a complete blackout of the Quebec province power grid in Canada, while one in January 1997 was the likely cause of the catastrophic failure of the Telstar 401 communications satellite. The photo shows the ejection of a large solar mass. (An ultraviolet image of the Sun is superimposed over the solar disk.)
CREDIT: SOHO (ESA & NASA)

Magnetic Storms

The Sun is ultimately the source of all weather within the solar system, but the Sun's influence on the Earth's space environment is largely conveyed through the solar wind—a gusty flow of particles that stream outward from the Sun at about a million miles per hour. The wind transfers solar energy into the Earth's magnetic field (the geomagnetic field), and during periods of intense solar activity, when the solar wind turns into a fierce gale, the amount of energy transferred gets proportionately larger. The transfer process is disruptive and catastrophic, somewhat analogous to the way a stretched rubber band snaps and transfers energy to your fingers, only in this case the result is an energized and distorted geomagnetic field. The enhanced geomagnetic activity is referred to as a magnetic storm.

Magnetic storms can last anywhere from hours to days, during which the intensity of relativistic electrons and the rate at which they pepper a satellite can increase several thousand-fold. Television, telephone, or radio reception can be disrupted, and the electrons can wreak havoc on satellite-transmitted data or, in what amounts to extraordinary bad luck, knock a satellite unconscious—forever.

If they know their "bird" is in for nasty weather, satellite operators can re-route communications or take other measures to protect the data streams. But usually they don't know because most satellites lack sensors to monitor the local space weather. And though there are satellites that monitor what's going on around them as they orbit, it's not a simple matter to use that data to infer the weather conditions along a different orbit. It's a tricky business.

That's where Reeves and his DREAM team can help.

DREAM

The whole point of the Dynamic Radiation Environment Assimilation Model, or DREAM, is to provide a snapshot of the belt's *global* electron environment, despite having sparse data that provides only a sample of the *local* environment surrounding a few satellites. If the Van Allen belt were relatively static and uniform, those local conditions would allow satellite operators to estimate the conditions facing their satellites. But conditions within the belt are too variable because the glue that holds the belt together is the dynamic and stormy geomagnetic field.

DREAM can provide that global picture. It takes whatever data is available and, in effect, combines it with data created from theoretical models of the geomagnetic field and the radiation belt. The technique called data assimilation then produces a more complete data set—an optimized solution that best represents the true electron environment surrounding the Earth out to about seven Earth radii (a distance of approximately 42,000 kilometers, or a little more than 10 percent of the distance to the moon).

It's a remarkable process, somewhat akin to using traffic conditions on the beltway around Washington, D.C., to describe traffic in downtown Chicago or along the tumbleweed-lined margins of Interstate 40 through New Mexico. Once DREAM has produced an output, an informed satellite operator can take actions as needed.

Says Reeves, "Even with partially complete physical models for the radiation belt dynamics and for the geomagnetic field, DREAM will do a surprisingly good job of calculating the local environment anywhere in near-Earth space."

A lite version of DREAM set up as a demonstration works so well that DREAM is already being regarded as a major asset for situational awareness. That's the government euphemism for everyone keeping their heads up to better anticipate emergency or hostile situations. And it may turn out that DREAM's ability to pinpoint hostile weather conditions will help everyone *keep* their heads should a critical satellite suddenly go *poof!*

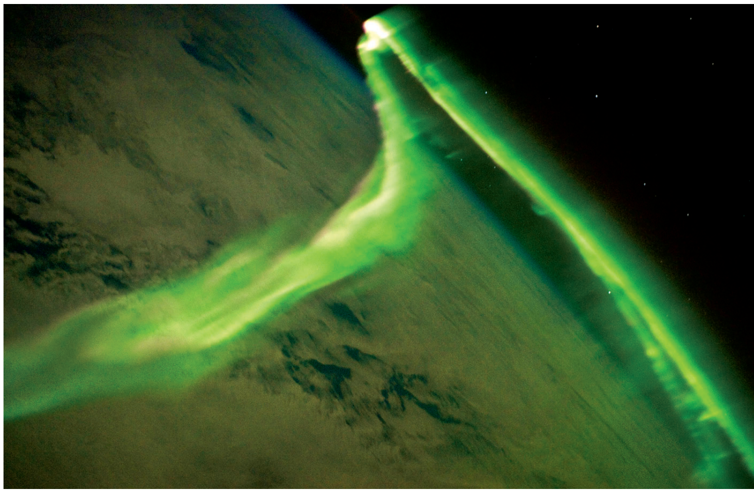
Increased space-situational awareness has certainly been a motivating factor in DREAM's development. But its software framework was designed to be modular and highly flexible, so it's a simple matter to test different theories about, say, electron diffusion in the Van Allen belt by swapping out different electron-diffusion modules. DREAM is as much a research tool for understanding near-Earth space as it is an aid to the satellite community. And there is indeed much to learn about that space.

The Radiation Belt Storm Probes, a matched pair of satellites designed to gather the data needed to understand the dynamics of the radiation belts, are scheduled to be launched in the fall of 2012. Los Alamos was heavily involved in justifying and defining their mission and in designing a suite of instruments carried on each probe, including building one of the instruments (the HOPE spectrometer). This is an artist's rendering of the probes in orbit.
CREDIT: NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

Surprise! Surprise!

Because the amount of energy transferred to the Earth's field fluctuates wildly, and because there are many ways to distribute that energy, the geomagnetic field is remarkably dynamic and complex.

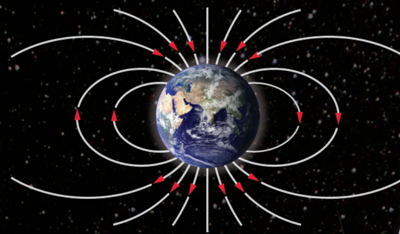
"It's a rotating, asymmetric field strongly coupled to a highly variable magnetized plasma [the solar wind]," says physicist and DREAM team member Mike Henderson. "It supports the Van Allen radiation belt, but the belt has its own dynamics—its particles gain energy, diffuse in and out. It inflates in size, even disappears sometimes."

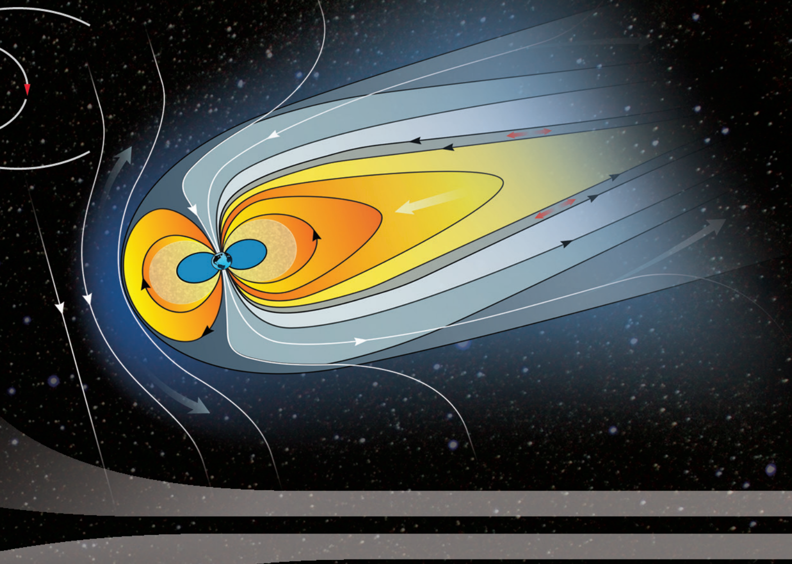


Particularly during magnetic storms, particles from the radiation belt can follow the Earth's field lines right into the Earth's upper atmosphere, where they collide with oxygen and other atoms. The atoms absorb the particles' energy and subsequently release it in the form of light, which stargazers observe as an aurora (the aurora borealis, or northern lights, in the northern hemisphere, and the aurora australis, or southern lights, in the southern hemisphere). The upper figure shows the aurora australis as seen from space; the lower shows the aurora borealis from the ground in Canada.
UPPER FIGURE CREDIT: ISS EXPEDITION 23 CREW, ISAL, NASA

Sweet DREAM Is Made of These

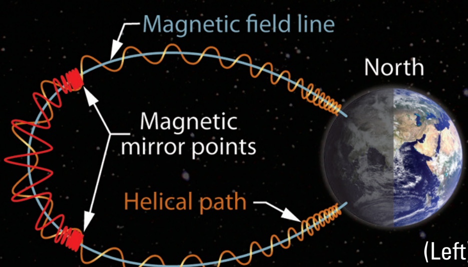
DREAM fills in the gaps of a sparse data set and produces a representation of the charged-particle environment surrounding the Earth. Some of the components that go into DREAM are illustrated below. To learn more, visit the DREAM website at dream.lanl.gov.

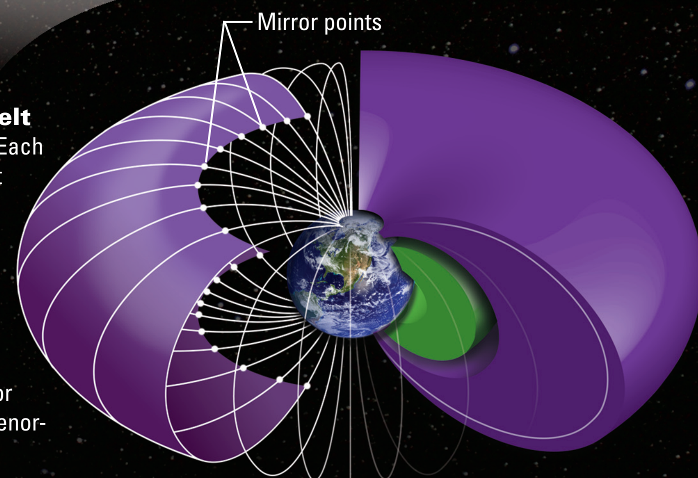




(Left) **The Geomagnetic Field** is often modeled as a simple dipole field, with field lines—invisible lines that run in the direction of the field—symmetric about the magnetic axis.

(Right) A more realistic model of the geomagnetic field includes the distortions caused by the solar wind, which compresses the daytime side of the field and drags the nighttime field far downwind. There is no symmetry about the magnetic axis. By adding more physical processes, such as a ring current that runs around the planet's midsection, the model can be made more complete, at the price of requiring more data to constrain the increased parameter space and significantly more time to perform the algorithms.





(Left) **The Van Allen Radiation Belt** is made up of energetic ions and electrons. Each particle follows a helical path that's centered around a geomagnetic field line. At a so-called mirror point, determined by the field strength and the particle's pitch angle, the particle reverses direction until it "bounces" off a similar mirror point in the other hemisphere. (The pitch angle determines how far a particle goes along a field line for one turn of the helix.)

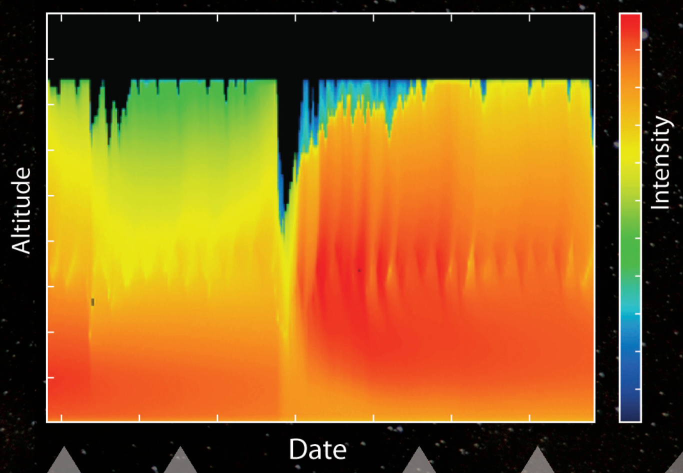
(Right) Particles also undergo a slow circular "drift" around the magnetic axis, so that particles of a given energy and pitch angle are trapped—constrained to occupy a mostly circular "drift shell" that's bounded by the north and south mirror points. With a distribution of particle energies and pitch angles, the result is the enormous, donut-shaped Van Allen radiation belt.

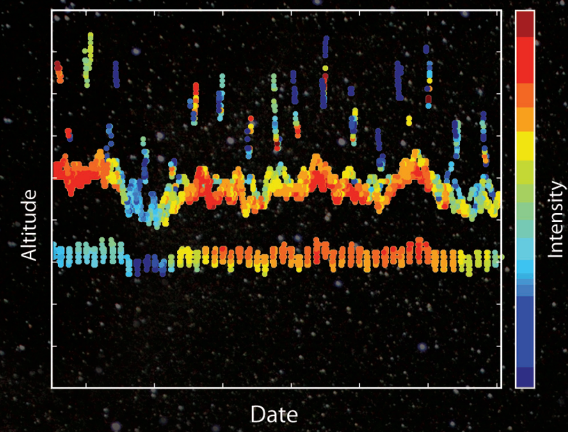
Evidently, there are aspects of the belt that are simply not understood.

For example, it's natural to suppose some correlation between the solar wind and radiation-belt electrons, and 30 years ago, the data indicated a nice, linear relationship between electron intensities and the solar-wind velocity. But after 30 more years of data collection, much of it gathered with Los Alamos instruments, the relationship is clearly nonlinear, with high electron intensities occurring for a wide range of velocities. This is not understood.

Then there is the mystery of the magnetic storms. It turns out to be only partially true that an influx of solar energy leads to higher particle energies. Reeves' team looked at several hundred storms to see how each affected the energy and population of electrons in the belt. The expectation was that more intense storms would result in more particles with higher energies. But often the storm had no effect, and 19 percent of the storms—nearly one out of five—actually depleted the belt. It's like a thunderstorm comes through and leaves your backyard drier than it was.

DREAM Output is the result of assimilating the data with results obtained from models of the geomagnetic field and the Van Allen radiation belt. It specifies the global particle environment, with electron flux given as a function of time and altitude.





Data Used by DREAM can come from a variety of instruments from any spacecraft, often in the form of electron flux (number of electrons per unit area, time, and energy) versus altitude and time. This data set comes from the GOES-13 satellite, a space weather data-gathering station in a geostationary orbit. (It moves at the same rotational speed as the Earth so it always has the same view of the planet.)

Manmade Radiation Belts can result from the injection and initial trapping of radiation from high-altitude nuclear explosions (HANE). DREAM contains a module, used for national security applications, for estimating the effects of the artificial belts. The picture shows a successful atmospheric nuclear test conducted by the United States in 1962. Known as Starfish, the 1.4-megaton device was detonated over the Pacific Ocean at an altitude of 400 kilometers. In the months following the test, seven orbiting satellites failed, presumably due to the addition of HANE radiation, which persisted for about five years.

A Prediction of Prediction

New light will be cast upon many of these poorly understood aspects of the belt come the fall of 2012 when NASA plans to launch the Radiation Belt Storm Probes (RBSP). The matched pair of satellites will probe all regions of the belt, gathering data that should revolutionize our understanding of the dynamic charged cloud. And once the belt and Earth's magnetic field are better understood, DREAM may transition from being a real-time specifier of the local space environment to a real-time forecaster of space weather. Then it may help prevent satellites from going *poof!* in the first place.

Whether DREAM gains predictive capability or not, Reeves and the team are in an ideal situation. "It's estimated that 99 percent of the visible universe is plasma," says Reeves, "and plasma interactions are the same whether they occur in the geomagnetic field or in jets shooting out from a supermassive black hole. It's a little difficult to probe the dynamics around a black hole, but we can launch probes into near-Earth space and watch those interactions as they are happening."

And they can do that while pursuing their DREAM. ❖ LDRD

—Jay Schecker